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HIGH DENSITY DIGITAL RECORDING ON MAGNETIC TAPE

by

P. F. Dingwall

G. R. Labrum

MINISTRY OF AVIATION
FARNBOROUGH HANTS

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ROYAL AIRCRAFT ESTABLISHMENT

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January 1965

HIGH DENSITY DIGITAL RECORDING ON MAGNETIC TAPE

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SUMMARY

The Report discusses the problems encountered in high area density digital recording on magnetic tape. Some aspects of the process of pulse recording are examined, and applied to the methods of digital recording in common use. A description is given of a system which offers advantages at high packing densities.

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1 INTRODUCTION

As aircraft become more complex, the number of measurements involved in testing them increases, and the accuracy requirements become more exacting. Measurements, which were made a decade ago with an accuracy of perhaps five per cent, are now required with a repeatable accuracy of better than one per cent, and the vast numbers of such measurements call for drastic changes in the existing methods of handling the data on the ground. Both these trends have increased the importance of airborne digital recording, with its inherent ability to provide a predetermined accuracy independent of the actual process of recording, and its potential for automatic handling of the recorded data.

However, the use of digital recording with present techniques involves a substantial loss in data packing when compared with existing analogue recording systems. This may be illustrated by a comparison of the data packing densities obtainable on a typical recorder using eight tracks on $\frac{1}{2}$ inch wide tape. With analogue recording, the use of time-multiplexed wide-deviation frequency modulation allows some fifty samples per inch per track; that is, 800 samples per square inch. For so called "double bandwidth" systems operating at a reduced carrier wavelength, this figure can be doubled with some loss of accuracy. By comparison, airborne digital systems using non-return-to-zero recording (see paragraph 6.2) typically operate at about 200 bits per inch of track and in an eight bit system, using parallel recording, some 400 samples per square inch are achieved. More advanced techniques can increase this limit to about 800 samples per square inch, which is comparable with the most conservative analogue systems.

There seems little doubt that the design of recording heads has reached a point when it is practicable to increase the number of tracks per inch of tape in both analogue and digital systems; but the number of tracks is decided by the system accuracy in parallel digital recording, and such systems are less readily "packaged" into an arbitrary number of tracks. It is evident that any major improvement in data packing must come from increased "bit-packing" along the tape tracks. This Report examines the problems of digital recording and replay with the aim of establishing the best methods for achieving reliable high bit density recording on magnetic tape.

2 THE RECORDING AND REPLAY PROCESS

The conventional head or transducer used for reading and writing on magnetic tape is the ring head, which is shown in Fig.1. Essentially it consists of a gapped toroid, in which the gap and surrounding core area can be

brought into close contact with the surface of the tape. During recording, flux lines, with a density proportional to the current in the winding, circulate in the core. Owing to the increased reluctance at the gap, some of them tend to spread into the space beyond the circumference of the core, and enter the tape surface. It is on the field represented by this small leakage flux that the recording process depends. When the current in the winding falls to zero, or when the field affecting the increment of tape in front of the gap is removed by the movement of the tape past the head, the induction in the tape falls to the remanent value corresponding to the applied field, and remains constant.

On replay, a proportion of the emergent, or "normal" flux lines, which leave the tape surface, link with the head winding, inducing a voltage across the winding proportional to the number of flux linkages changing in unit time. The output from the head on replay falls to zero at zero recorded frequency, and in a practical system noise sets the lower limit to the frequency which can be reproduced. Furthermore, the replay process fails at wavelengths which are much longer than the head pole faces in contact with the tape, and also at wavelengths which are sufficiently short to approach the gap length, when flux cancellation reduces the output, so that with a perfectly defined gap, a null occurs at a wavelength equal to the gap length. The null is repeated at integral sub-multiples of the gap length, but for all practical purposes the head response is confined to wavelengths longer than the first null. A similar mechanism of flux cancellation also results in loss of signal at wavelengths which are integral sub-multiples of the pole face of the head in contact with the tape, and various means are employed in the design of replay heads to reduce this effect.

The remanent flux on the tape is not linearly related to the current in such a ring head, and artifices such as bias recording^{1,2} are used in order to obtain a linear transfer characteristic, where this is mandatory. In systems which rely on the recording of pulses, or carriers in which the signal cross-overs convey the information, no attempt is made to effect a linear recording, and the tape is driven into saturation in either sense by passing a current of sufficient amplitude through the head. This technique, which can define on the tape the three states of positive and negative saturation and zero magnetisation, is the only recording method considered in this Report.

3 RECORDING RESOLUTION

3.1 Resolution of the recording medium

The ultimate limit to the resolution of a non-homogeneous recording medium must lie in the particle size. Photographic grain is an obvious example. Magnetic oxide tape contains particles of ferric oxide about 40 micro-inches long, embedded in a matrix of non-magnetic binder. The particles are normally oriented in the direction of tape motion, and it is difficult to see how recordings could be made with flux changes at intervals of less than the particle length. Thus for linear densities of more than about twelve thousand cycles per inch, some alternative form of medium must be sought.

The particle size is not the only limitation however. Irregularities in the surface of the medium, which with present tapes average some twenty micro-inches, cause a wavelength dependent loss on replay³ which virtually eliminates the replay of wavelengths comparable to the head-tape separation. Self-demagnetisation can obviously affect short wavelength recording, although it seems difficult to dissociate it experimentally from other effects. Again, the recording of such wavelengths presupposes that the recording is confined to a very thin layer, since magnetisation at any appreciable depth results in a spread of flux lines at the surface which is sufficient to degrade the resolution of a flux reversal, and cause demagnetisation of adjacent wavelengths nearer the surface. In this connection the advantages of a thin homogeneous medium have been demonstrated by recent work on thin metallic films⁴ with a thickness of 5 to 10 micro-inches. Tapes at present in use employ oxide coatings with a thickness of 0.0005 inch or, more recently, 0.0002 inch. The depth of such coatings is comparable to the wavelengths in current use for frequency modulation and "direct" (with bias) recording. Such tapes must inevitably show poor resolution, at high digital packing densities, when compared with thin coating or thin homogeneous recording media.

3.2 Resolution of the magnetic head

The use of high density recording is clearly subject to a limitation imposed by the replay gap. It is evident that in order to obtain a replay signal, the number of flux lines linking with the core must be a function of time, or distance along the tape. At wavelengths approaching the replay gap width, the flux lines leaving the tape surface tend to integrate to zero across the gap, and little or no output is obtained from the head. This "gap loss" effect has frequently been derived⁵ for a perfect gap and sinusoidal flux distribution, although this is not strictly applicable to pulse recording.

Some doubt exists as to the influence of the recording gap on packing density, and the authors have attempted to investigate some aspects of the recording process below. There is evidence to show that the recording process imposes a more severe restriction on the packing density than the replay process.

4 PULSE RECORDING

4.1 The effect of recording current amplitude

The dependence of the replayed signal amplitude upon recording current in short wavelength recording on magnetic oxide tapes is well established. At long wavelengths, the replayed signal amplitude rises to a maximum as the recording current is increased, and then stays constant. This condition apparently indicates tape saturation. At short wavelengths a different effect is observed. As the current is increased, the replayed amplitude rises to a maximum, and then falls again before the current corresponding to tape saturation is reached. The effect is shown in the curves of Fig.2, and it is evident that some additional factor intervenes at short wavelengths and results in a loss of signal at high currents, so that an optimum current exists. The curves of Fig.2 were taken using tape with a coating thickness of about 0.0005 inch, and at a wavelength of 0.001 inch this thickness is comparable to the distance between flux reversals, so that the section of oxide available for magnetisation is roughly square. It can be argued therefore that the recording current effect is attributable to the same cause as the loss of resolution in thick media discussed in paragraph 3.1. As the recording current is increased, the distance from the head face, at which a field of given intensity occurs, increases. This increases the effective depth in the medium at which significant remanent magnetisation is left, and the replay signal is diminished by the self-demagnetisation inherent in magnets of low length/width ratio. Loss of signal will occur where flux lines, corresponding to the same recording current, are generated at different depths in the medium and leave the surface at different points.

4.2 Flux distribution on the recording head

Apart from the demagnetisation and loss of resolution occurring in the medium at high recording currents, there are effects associated with the recording head itself. The flux lines do not leave the head in the immediate vicinity of the gap, but emerge from the head face at distances up to several gap lengths from the actual gap.

The use of a marker, or indicator of magnetic powder, can give a qualitative assessment of flux distribution by defining a cross section of flux above the tape or head from which rough measurements can be made. A suitable marker can be made with a suspension of carbonyl iron (with a particle size of a few microns) in a very dilute solution of shellac in alcohol. If a thin polyester film is stretched over the head surface, a cross section of the flux pattern at a distance from the head is obtained by depositing this marker on it. By varying the recording current, it can be observed that the marker spreads further as the field is increased, showing that the flux pattern alters with increased flux density in the head. Two such sections are shown in Fig.3, which are microphotographs taken with polyester film 0.00025 inch and 0.001 inch thick respectively. In each case the head current was adjusted to the value which gave the maximum replay amplitude for a recorded wavelength of 0.001 inch. The spread of flux in the upper photograph, at a distance of 0.00025 inch above the head face, covers some 0.004 inch, or sixteen times the recording gap width; at a distance of 0.001 inch it has fallen to 0.003 inch (lower photograph), and at a distance of 0.0015 inch (not shown) the marker only just defines the gap. These observations suggest that the field pattern consists of simple loops of flux emerging from the gap edge and head face up to about 0.002 inch from the gap on either side, and extending to a maximum height of perhaps 0.0015 inch to 0.002 inch.

The intensity of the field at the gap region of a recording head will decrease along the head face on either side of the gap, and decrease vertically above the gap. If a length d along the head face defines the region in which a field $H \geq H_0$ exists, where H_0 is the minimum field which can leave a remanent induction on the tape significant in terms of replay amplitude, then it is convenient to assume the field distribution of Fig.4, in which the boundary lines define the region in which a significant field exists. In this diagram, d and a are unknown but it can be assumed that they bear a definite relationship to the distribution observed by the marker technique.

4.3 The flux pattern on the tape

Assuming a field distribution of the type shown in Fig.4, the process of recording a unidirectional or return-to-zero pulse can be examined. Let the pulse be of duration t , so that the tape moves a distance Vt in this time at a velocity V . The rise and fall times of the current in the head windings are insignificant compared with t . In Fig.5, as the current rises to its maximum value I , the head field increases to a value greater than H_0 everywhere within

the triangular region; then, as the tape moves past the head, the field applied to it falls to zero, leaving a remanent magnetisation which starts at a distance $d/2$ before the gap at switch-on, and ends a distance $d/2$ after the gap on switch off. The effective length on the tape of a pulse of duration t is thus

$$L = d + Vt \quad .$$

At each end the remanance falls to zero over the distance $d/2$ while it retains the value corresponding to the maximum applied field (i.e. saturation or near saturation) over the distance Vt . In the regions $d/2$ therefore, in which the magnetisation in the tape is changing, flux lines leave the surface of the tape and re-enter it at the other end of the pulse.

When a recording current waveform symmetrical about zero is used, there can be no increase in pulse length. Any increase would imply a change of frequency. The magnetic pattern on the tape for a symmetrical current can be deduced by considering it as the sum of two unidirectional currents of opposite polarity. In Fig.6, the region a-c on the tape is initially magnetised by the first pulse as shown in Fig.6(o). The region b-c is then subjected to the maximum reverse recording field and, assuming saturation, is completely re-written. The region a-b is subjected to a reverse field which decreases from a maximum to zero from b to a. This field falls to zero at all points as the tape moves, leaving in a-b a remanent magnetisation changing from a maximum of one sign to a maximum of the other sign. Thus the flux reversal region a-b is again of length $d/2$, and is written behind the recording gap when the current reverses. The point of zero induction within the region a-b depends upon the magnetic properties of the oxide and, in particular, on the ratio of coercive force to maximum applied field. Under normal recording conditions there is marked asymmetry, and the flux reversal point is displaced in the direction of tape motion. The effect of this may be seen on the replay pulse waveform (see paragraph 5.2).

In order to obtain a quantitative value for $d/2$, the surface of a recorded tape was treated with marker. Fig.7 shows microphotographs (X 100) of (a), the tape surface and (b) and (c), polyester films superimposed on the tape so as to obtain sections at 0.00025 inch and 0.001 inch separation. The tape was symmetrically recorded with a 0.008 inch wavelength at the current for optimum replay signal amplitude. The marker indicated that the majority of flux lines left the tape over a region 0.001 inch wide (Fig.7(a)), so that a value of $d/2$ of about 0.001 inch is indicated. However, a smaller number of

lines leave the tape over a region 0.002 inch to 0.003 inch wide, and these can be of significance in certain forms of digital recording. The assumption of a triangular field boundary on the recording head is not exact, and the actual field probably has a long "skirt" extending to perhaps 0.003 inch on either side of the gap. This is in reasonable agreement with the flux pattern indicated on the head face (paragraph 4.2).

In Fig.7(b) the flux lines are still roughly normal to the tape surface, while in Fig.7(c) a strong component parallel to the tape has appeared. These photographs suggest a fairly simple flux pattern, with flux leaving the tape within a broad region around each crossover and taking paths to adjacent crossovers, parallel to the tape surface, in a plane about 0.001 inch above it. The flux pattern on the tape thus consists of regions of normal or emergent flux about 0.001 inch wide, with an area of much lower density flux extending to 0.002 inch or more. This region of emergent flux represents the maximum resolution which can be obtained from a single crossover with the tape and heads used in these experiments.

5 THE REPLAY OF PULSE RECORDINGS

5.1 Flux linkages with the head

In a conventional replay head, the output is derived from changes of flux linkage with the head windings and its amplitude is proportional, at any instant, to the rate at which lines are linking or unlinking with the windings.

The mechanism of replay is illustrated for a single flux line in Fig.8. A line which leaves the tape, in a region of emergent flux which defines a crossover in the recording current, finds its way to an adjacent region by taking a path through the head core. The path can be either along the head face, or via the core windings. A line will tend to take the former path until its point of emergence has traversed about half the gap. At some point after this, the reluctance of the path via the winding becomes lower and the line then links with the winding, inducing an increment of output voltage. Similarly, when the other end of the line is reached, the linkage ceases and the line again takes a path via the head face.

Each region of emergent flux, defining a crossover, consists of lines linking with regions on either side along the tape, (paragraph 4.3). At the flux reversal position, within these regions, the lines divide, those before this position linking with a previous region, and those after it linking with a following region. The flux reversal position coincides with the point of zero

remanent induction in the tape. Consider the process involved in soanning such a region with a replay head. Between the regions the maximum number of lines are linked with the windings. As the gap approaches a flux reversal position, an increasing number of lines are becoming unlinked, and the output voltage rises. At the centre of the flux reversal, where the output voltage has reached a maximum, this process ceases and new lines are becoming linked with the windings in the opposite sense; these lines therefore contribute to the output voltage in the same sense as before, and the latter only changes as the number of new lines linking begins to decrease, falling to zero as the gap leaves the region. Typical recording and replay pulses are shown in Fig.9. These photographs also show the increase in pulse length resulting from a unidirectional recording current (paragraph 4.3). In Fig.9 the recording currents are unidirectional pulses of durations corresponding to distances on the tape of (a) 0.003 inch, and (b) 0.001 inch. In each case the separation of the replayed pulses is increased by about 0.001 inch.

The reasoning illustrated in Fig.8 shows that, at wavelengths longer than the gap, the effective gap with which the head scans the flux distribution on the tape is in fact narrower than the physical gap; but at very short wavelengths the distance between flux reversals becomes comparable to the gap length and the reasoning breaks down. With conventional 0.00025 inch gap heads this occurs at a wavelength of about 0.0005 inch. But the regions of emergent flux which define a crossover in the recording process begin to overlap at wavelengths of 0.002 inch or greater. The effect of this is considered below.

5.2 The replayed waveform

The above reasoning has shown that the output waveform consists of a pulse at each crossover region, the polarity of which reverses as the normal flux reverses at successive crossovers.

If V_o is the head output voltage

$$V_o = K \frac{d\phi}{dt} = K \frac{dx}{dt} \times \frac{d\phi}{dx}$$

where K is a scaling factor constant at long wavelengths.

At a constant tape speed V,

$$V_o = K V \frac{d\phi}{dx} .$$

The output of the head at constant tape speed is thus proportional to the area density, in any region, of normal or emergent flux. The amplitude of the pulses are proportional to tape speed, but independent of pulse wavelength on the tape below the wavelength at which successive crossover areas begin to overlap. When this occurs, two cases can be distinguished, depending upon whether the crossover regions overlap by more than half their area or not, so that the regions of maximum flux density overlap. In Fig.10 the lines XXX represent the regions of maximum normal flux density for each crossover. When the overlap is less than $d/4$ (assuming no asymmetry in the flux pattern) the remanent induction in the region a-c due to the first crossover is modified by the second crossover. In the region a-b the first applied field is greater than the second. In the region b-c the second field is the greater. At b the two are equal. Owing to the shape of the hysteresis curve, however, the region in which the normal flux reverses its sense is shifted from b in the direction of tape motion. In the region a-c the flux is everywhere less than it would have been without overlap. The peak flux density in the crossover regions is unaltered however, so that the average flux density is increased by the overlap, increasing the slope between signal peaks above that encountered in a single replay pulse.

When the overlap exceeds about $d/4$, the peak flux density is reduced as well, and the region of peak flux density is moved laterally. The flux on the tape is now the result of the application of three successive fields in the region of peak flux density. The signal amplitude falls as the overlap increases and, when the current crossovers are irregularly spaced (as they are in typical digital bit patterns) the replayed peaks are shifted from their correct position.

An approximation to the replay waveforms can be obtained for any rectangular wave recording by graphical superposition of the replay pulses due to a single crossover or flux reversal. The resulting waveform is the sum of the individual waveforms, and the method gives reasonably accurate results when the overlap of the crossover areas is less than $d/4$. The replayed waveforms shown in Figs.13 and 15 are drawn in this way. But at the wavelengths where the flux on the tape is due to the application of three or more successive fields the method is of little value.

In Fig.11 is shown photographs of the recorded and replayed waveforms at different packing densities. In (a) the individual pulses, obtained from flux reversals at intervals of 0.005 inch on the tape, are about 0.001 inch wide; but the "skirts" extend to about 0.003 inch. In (b) the main regions are just

meeting, at a packing density of one thousand reversals per inch and the inflexion corresponding to the region a-o in Fig.10 can be seen. In both (a) and (b) the asymmetry of the pulses is evident. At 2000 flux reversals per inch (Fig.11(c)) the overlap includes the peaks, and the amplitude of the response is beginning to fall.

This mechanism results in the characteristic replay amplitude/frequency graph for rectangular wave recording shown in Fig.12. The replay gap loss for a sinusoidal recording is plotted in the same scale for comparison.

6 APPLICATION TO DIGITAL RECORDING

The reasons for the flux pattern on the tape may lie in the distribution of the field pattern on the head, as suggested in paragraph 4.3, or it may be due to the effects of recording on a medium whose thickness is not small in comparison with the recorded wavelength, or to a combination of these effects. Whatever the cause, the conventional tape and heads used in these experiments produce a flux pattern in which the resolution of each flux reversal or cross-over is degraded to a width of 0.001 inch or greater; and it is in the light of this information that the various forms of pulse code modulation are considered below.

6.1 Non-return-to-zero recording

A symmetrical magnetisation is applied to the tape either by reversing the current through the head winding or by applying a standing bias which holds the tape near saturation in one direction when the recording current is zero. When used in its simplest form (Fig.13(a)) one state of magnetisation defines a "nought" in the code and the other a "one". This method of recording is unsatisfactory, since the replay head recognises only normal flux and not tape magnetisation. An output is obtained only when the state changes, and the replay system must remember the previous state until the next output pulse. A single error then reverses the code. The non-return-to-zero system more commonly used with tape (Fig.13(c)) writes a "one" as a flux reversal, while no change represents a "nought". Decoding involves the recognition of the presence or absence of a pulse in each bit cell (as defined by the clock signal) and one method of decoding is indicated in the block diagram of Fig.14. The system uses only one flux reversal per bit, but is not suitable for high density recording. The limitation arises from the difficulty of defining a "nought" between the two "ones" at high packing densities. For example, at one thousand bits per inch the flux reversal regions on the tape are touching, and there is no defined region of zero normal flux. Even at packing densities well below

one thousand per inch, the replay signal in a "nought" cell only crosses zero at one instant, instead of remaining zero for a period of time. This condition calls for very accurate timing of the sample gate in Fig.14, and skew problems in the tape transport limit its application in parallel recording to relatively low packing densities. With a more sophisticated technique, in which the change of slope at a peak in the replay waveform is detected and used to generate a "one" pulse, higher packing densities are possible, but the system is limited to less than one thousand bits per inch, is dependent upon input waveform, and precludes the use of limiters.

6.2 Return-to-zero recording

In this form of recording, illustrated in Fig.15, the two states of the code are recorded by means of unidirectional pulses of opposite polarity. Since each bit is uniquely defined, the code is self-clocking, but the replay mechanism results in two pulses of opposite polarity for each recorded pulse. Decoding involves the recognition of the relative order of successive pulses. At high packing densities the "pulse-spreading" effect discussed in paragraph 5.1 reduces the regions of zero magnetisation, and with an equal mark-space ratio these disappear first. At 500 bits per inch (Fig.15(b)) the zeros in the code are lost, and any limiting action results in the loss of the self-clocking properties. It is interesting to consider the effect of limiting on this waveform (Fig.15(c)).

The sketch shows that a waveform is obtained which, if sampled at the appropriate part of each cycle, exhibits positive or negative polarity depending upon the state of the code. It may be asked therefore, whether this waveform cannot be generated by simpler means and used to convey the code at high packing densities.

6.3 Phase reversal recording

The code to which RZ recording degenerates at high packing densities (see Fig.15(c)) has been described as "phase modulation" recording⁶, but the authors suggest the less ambiguous title of "phase-reversal" recording. "Frequency doubling" recording⁶ is very similar, the only difference lying in the definition of the bit cell. Comparison of this waveform with NRZ recording shows that the former has twice as many flux reversals per inch at a given packing density, and it may be for this reason that it has not been greatly used. The state of the code is defined by the polarity of the carrier replayed from the tape when the latter is compared with a clock signal, the phase of which does not alter. Since the information is carried by the polarity of the carrier, the only effect

resulting from overlapping of the flux reversal regions is a loss of amplitude when these regions overlap by half their width or more. This effect then progressively reduces the signal amplitude as the packing density is increased until system noise sets a limit to the amplification employed in the limiters. The recovery and limiting of frequency modulation carriers presents identical problems to this form of digital recording; densities of two thousand five hundred cycles per inch are currently employed at the upper limit of deviation in wide band frequency modulation recording using "narrow gap" (0.0001 inch) heads. In a practical parallel digital recording system however, a limiting packing density significantly below this figure is set by dynamic tape skew. Nevertheless, the tolerance to skew of phase reversal recording is appreciably greater than with conventional NRZ recording, since a full half bit is available for sampling, whereas with high density conventional NRZ recording a "nought" is only momentarily defined.

6.4 Two-frequency recording

This system was tried by the authors during development work as an alternative to the phase reversal system. A cycle of the clock frequency defines a bit in one state of the code, and two cycles of twice the clock frequency define a bit in the other state. The replayed signal, after amplifying and limiting, can be applied to a discriminator which measures the duration of each cycle, so that two different output levels define the code. Subsequent examination of the method of operation of this type of discriminator showed that since it relied for its operation on defining a crossover, or change of signal polarity, decoding could be equally well effected by the sampling technique used for the phase reversal system (apart from skew tolerance, which is reduced by this method). The decoding of this system is further discussed below.

7 CHOICE OF A SYSTEM

The existence of flux reversal regions of a finite width which are not short compared to the bit length militates strongly against any system which has to rely on the recognition of areas of zero normal tape flux; such areas rapidly become crowded out and disappear in high density recording. This defect is common to all systems based on variants of the NRZ recording system. Moreover, it has been demonstrated above that RZ recording degenerates into phase reversal recording at high packing densities. With phase reversal recording, the only penalty resulting from high packing is a progressive loss of signal amplitude as the packing density is increased. Moreover, since a full half bit is available for gating on replay, the system is more tolerant of tape

skew than the NRZ system at a given packing density. A comparison between the phase reversal and two frequency systems shows that the latter employs twice as many crossovers per inch of tape as the phase reversal system, with little compensating advantage. The phase reversal system thus emerges as the obvious choice for any system in which high packing densities are required.

8 WAVEFORM GENERATION AND DECODING

8.1 Phase reversal system

Some of the means employed to generate this waveform seem to be unnecessarily complicated, and a circuit has been devised whereby two rectangular waves in anti-phase are generated from the same clock generator. The head current is then obtained by gating one waveform or the other into the head drive circuit, depending upon the state of the digital code at that time. Changes in the code are delayed into synchronism with the clock waveforms by means of a synchronising gate. The arrangement is shown in the block diagram of Fig.16. Fig.17(a) shows the recording current waveform and replay signal waveforms for two changes in the code. In Fig.17(b) the replay signal recorded with a single code change at 1000 bits per inch has been photographed beside the clock track recorded on the same tape; the reversal of signal phase can be seen. The recording current and replay signal after limiting have similar waveforms; the signal is decoded by sampling with a pulse, derived from the clock track, which is delayed by one quarter bit from the beginning of each cell, and switching a binary store into the state indicated by the signal polarity.

8.2 Two-frequency system

The recording current for this system is generated in the same way as the phase reversal system, by gating one or other frequency into the recording head, depending upon the state of the code. This system can be made self-clocking and self-decoding. The method of decoding is identical to that used in phase reversal recording, except that the sampling pulse is delayed by $\frac{3}{8}$ bit instead of $\frac{1}{4}$ bit. The decoding waveforms are shown in Fig.18. Because of its self-clocking properties, the system appears to offer some advantages for serial recording on wire, but no practical work has been carried out in this direction.

9 PRACTICAL LIMITATIONS

The two factors which set a limit to the packing density in these two systems are loss of signal amplitude and skew. In the two-frequency system, one state of the code results in flux reversals at four times the bit rate, and the replayed signal amplitude at 1000 bits per inch is marginal with

0.00025 inch gap heads. A practical packing density, with the present standard tape and 0.0025 inch gap heads, is about 500 bits per inch. Skew is not a direct limitation with this system because of its self-clocking properties, but some complication of the replay electronics is necessary in parallel recording in order to identify words. With phase reversal recording, skew is likely to be the ultimate limitation; the signal amplitude limit may perhaps be extended to shorter wavelengths by the use of narrow gap heads and suitable tape coatings, but dynamic skew is ultimately controlled by the quality and mechanical uniformity of the tape itself and with present materials it is doubtful if this dynamic skew can be consistently reduced below some 0.5 min of arc. As the packing density is increased, it becomes necessary to reduce the distance between clock and signal tracks in parallel recording and the use of narrow track recording heads with a larger number of tracks in the unit width of the tape can alleviate the skew problem at the expense of signal amplitude. The severe vibrational environment to which airborne tape transports may be subjected is likely to increase the skew problem still further. The machining tolerances of the tape guiding surfaces, such as the flanges on guide rollers, allow a greater theoretical skew tolerance than is obtained in practice. This arises because tape is largely self-guiding and assumes a stable position in the tape path, provided all contact surfaces are true and parallel within sufficiently close tolerances. Under vibration however, loss of alignment can shift the tape into different positions, and attention to the rigidity of the guiding surfaces is essential in the design of the transport. In addition to the skew limitations, the available sampling time is inevitably reduced in the replay electronics by the rise times of the signal circuits and by changes in mark-space ratio resulting from imperfect limiting. The presence of transient terms in the replay signal with certain bit patterns can also cause shifts of mark-space ratio with perfect limiting and some simple equalisation before limiting is necessary with either type of recording.

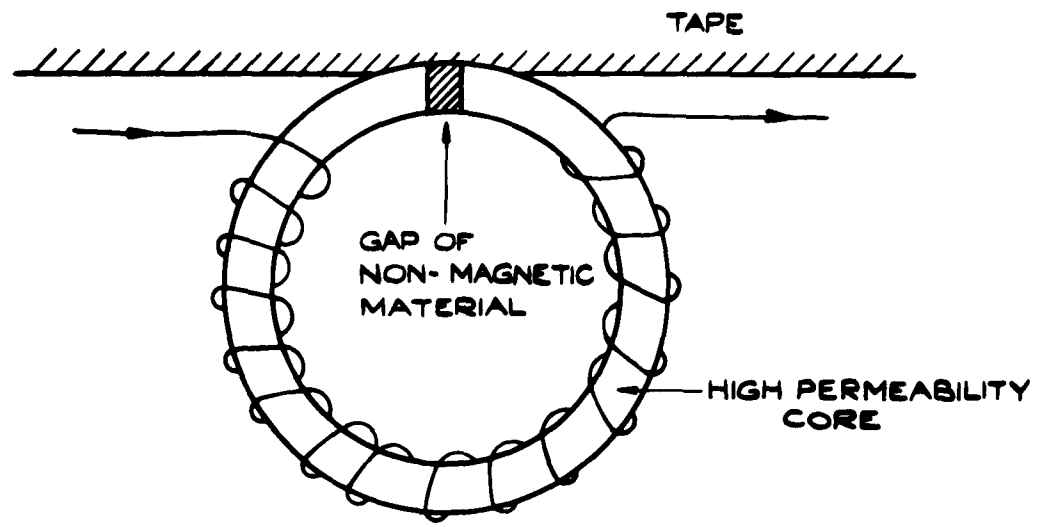
10 CONCLUSIONS

There seems little doubt that phase reversal recording, or some similar system employing the sign of the amplitude of the recorded signal, offers the most simple approach to high density recording at present. Since the work outlined above was confined to one type of standard magnetic head and one type of recording tape, there is obviously a need for further study of these items in the recording process. In particular, the use of narrow gap recording heads, means for controlling the spread of the recording field on the head face,

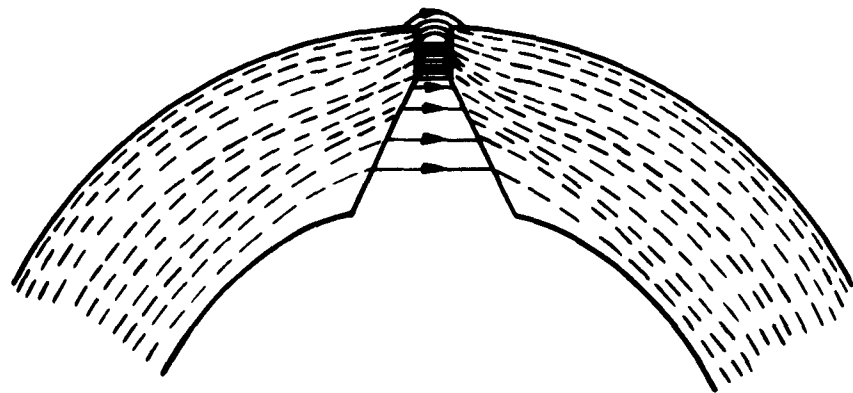
and the effect of thinner coatings are all aspects of the problem demanding attention. A quantitative approach to the investigation of skew problems is also desirable.

REFERENCES

<u>No.</u>	<u>Author</u>	<u>Title, etc</u>
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2	R.E. Turner	Magnetic recording with a.o. bias Proc IRE, Feb 1951
3	R.L. Wallace, Jnr	The reproduction of magnetically recorded signals Bell System Technical Journal Part 2, 1951, 30, 1145
4	G. Bate J.R. Morrison D.E. Speliotis	High density digital recording on thin metal surfaces International Conference on Magnetic Recording, IRE, July 1964
5	H.G.M. Spratt	Magnetic tape recording Heywood & Co, p.78
6	G.L. Davies	Magnetic tape instrumentation McGraw Hill Publishing Co, p.56-57



(a) RING HEAD



(b) DETAIL OF GAP
NOT TO SCALE

FIG.1 (a&b) RING HEAD

Fig.2

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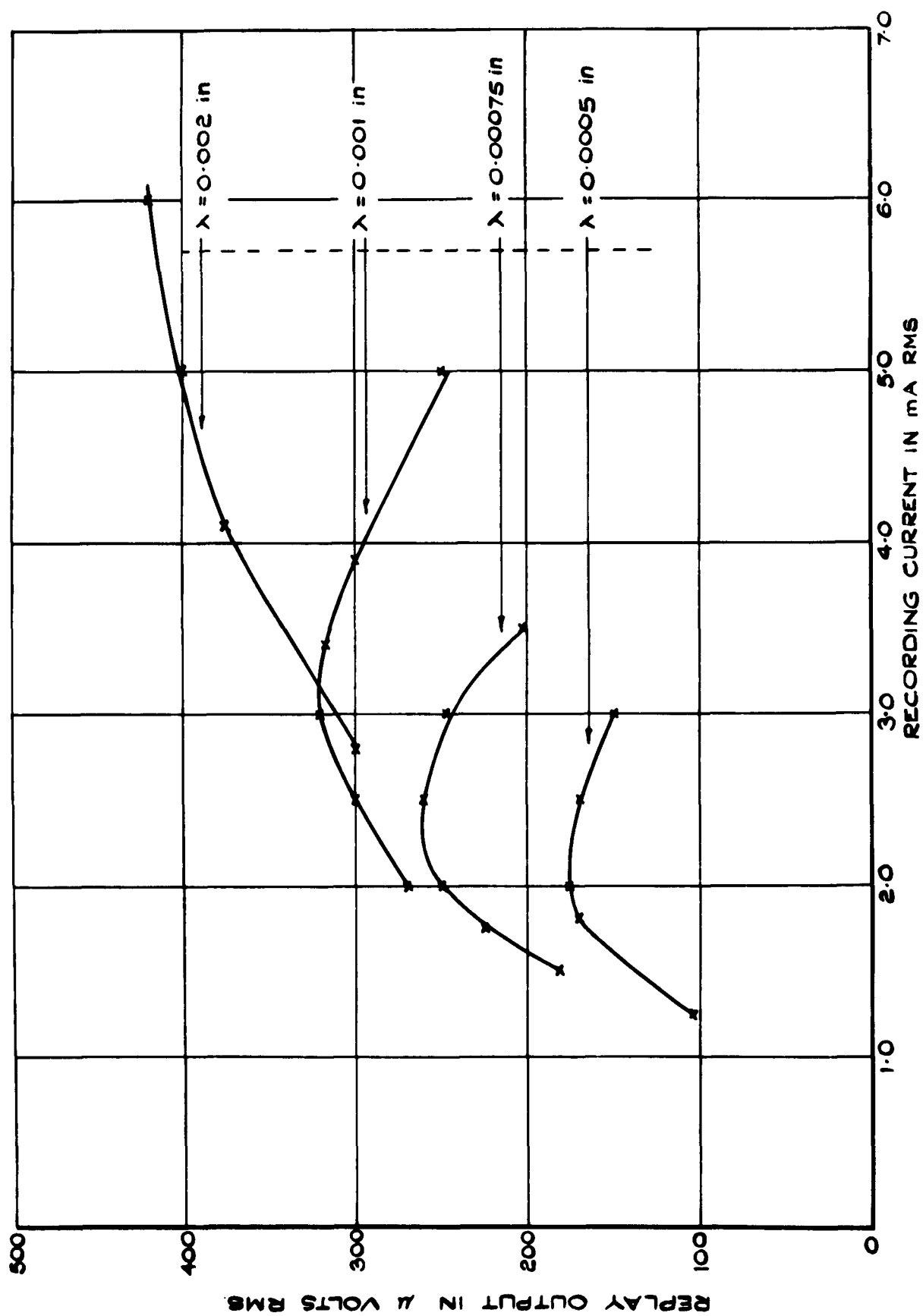
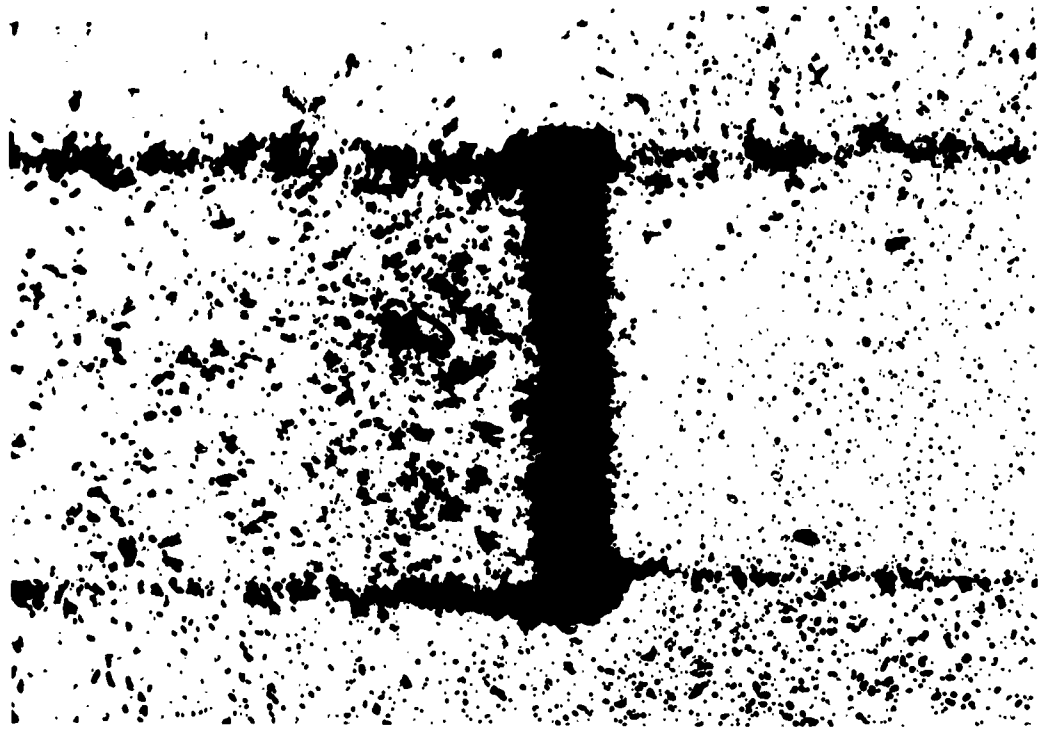
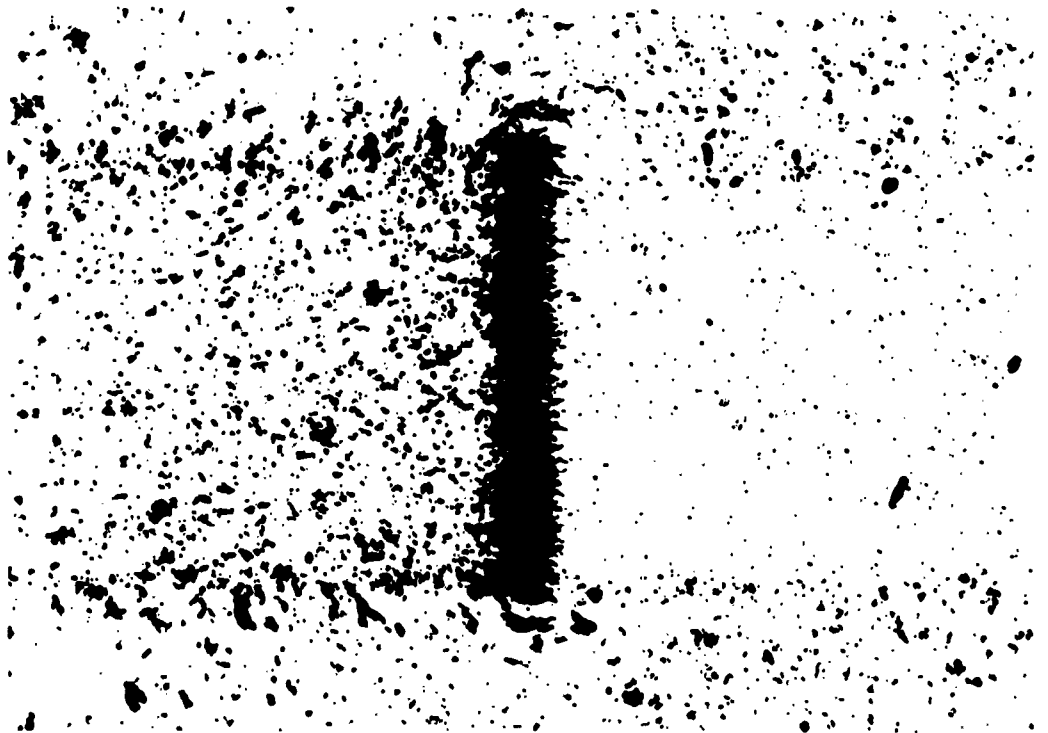


FIG.2 VARIATION OF REPLAY VOLTAGE AMPLITUDE WITH RECORDING CURRENT



a. Section 0.00025 inch above head face



b. Section 0.001 inch above head face

Fig.3 Flux distribution on a 0.00025inch gap recording head

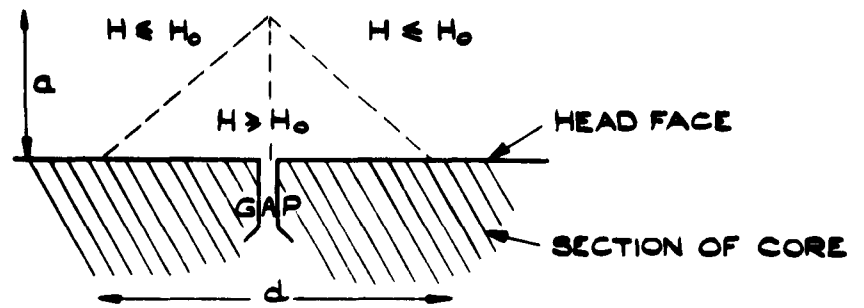
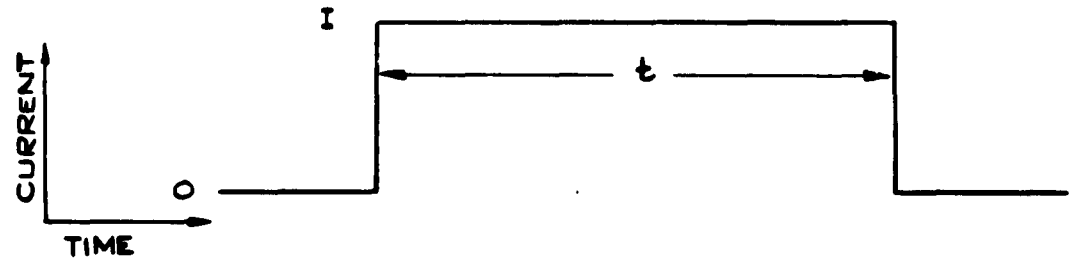
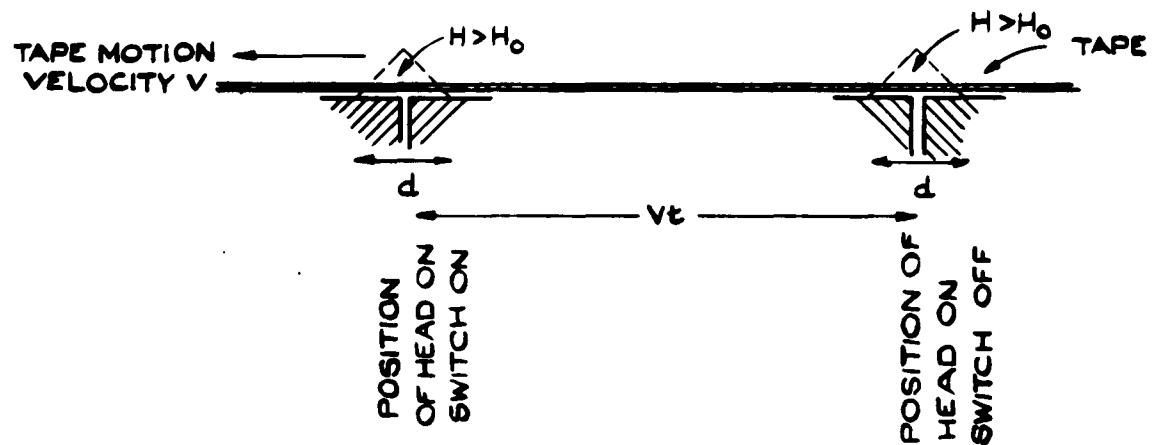


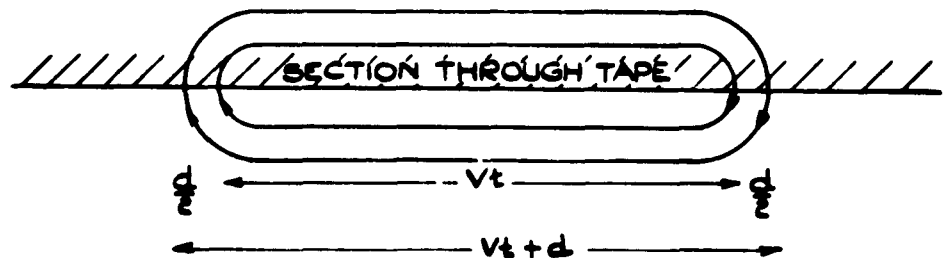
FIG.4 FIELD DISTRIBUTION ABOVE RECORDING HEAD



(a) RECORDING HEAD CURRENT



(b) FIELD DURING RECORDING



(c) REMANENT FLUX

FIG.5 (a-c) RECORDING A UNIDIRECTIONAL PULSE

Fig.6

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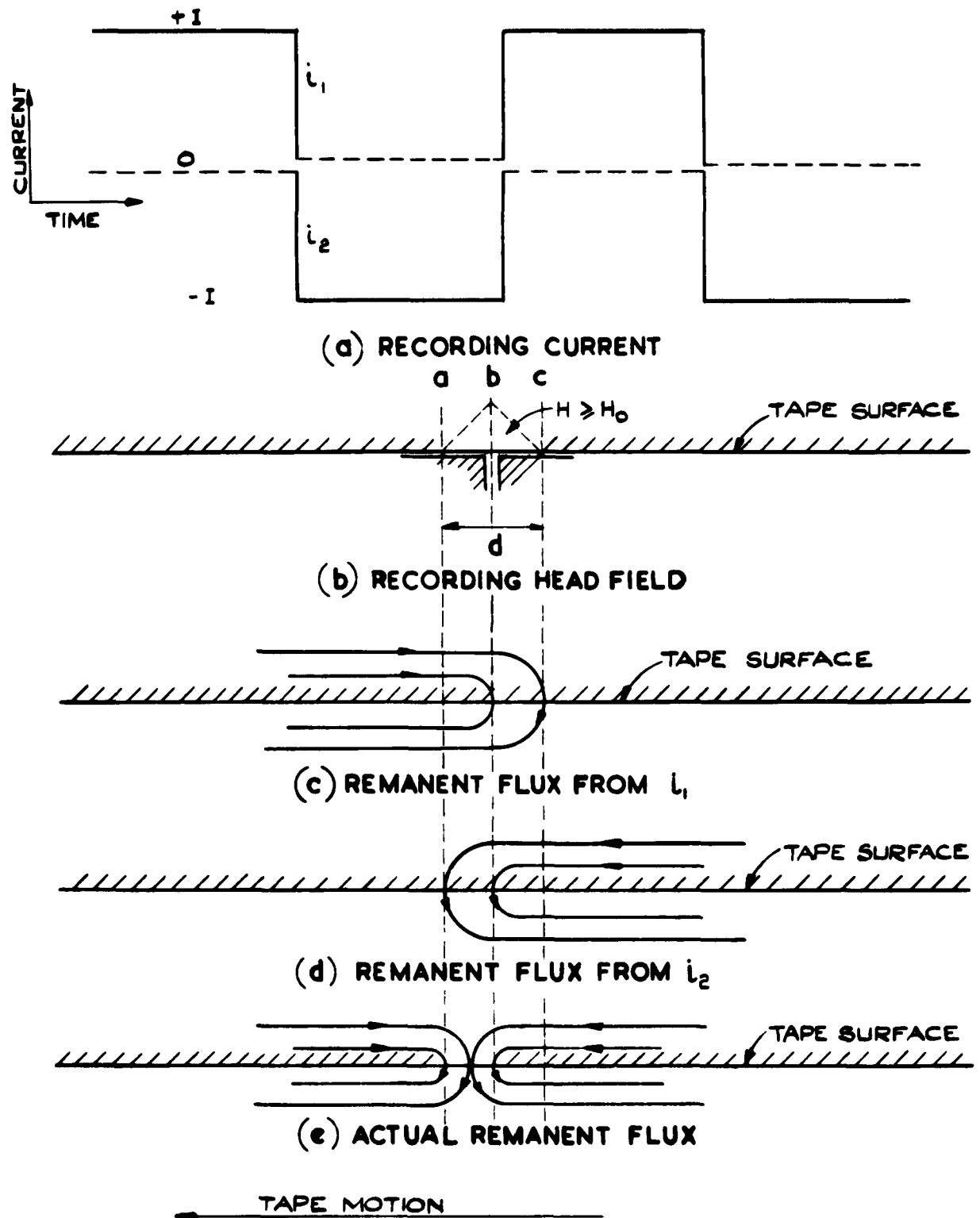
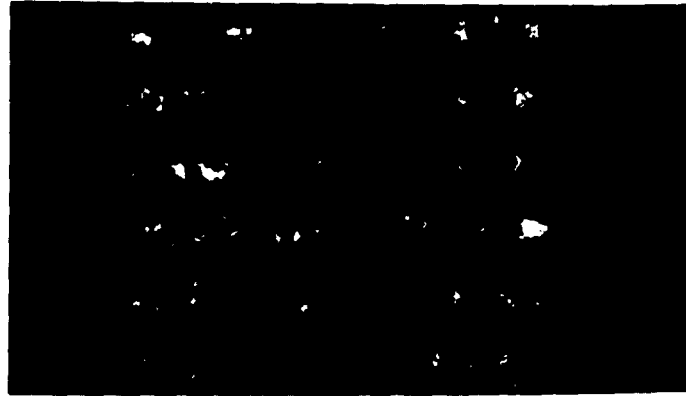
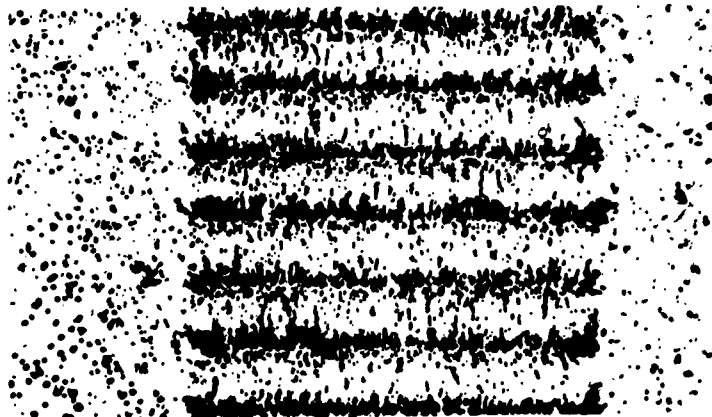


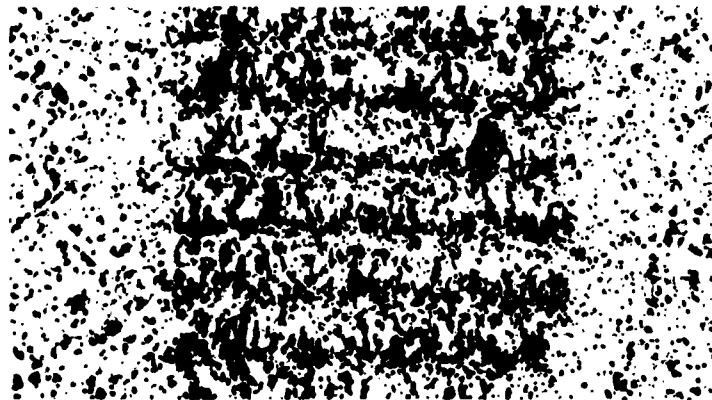
FIG.6 (a-e) RECORDING A SYMMETRICAL PULSE



a. Surface of tape



b. Section 0.00025 inch above tape



c. Section 0.001 inch above tape

Fig.7 Sections of normal flux for a symmetrical rectangular wave recording. Wavelength 0.008inch

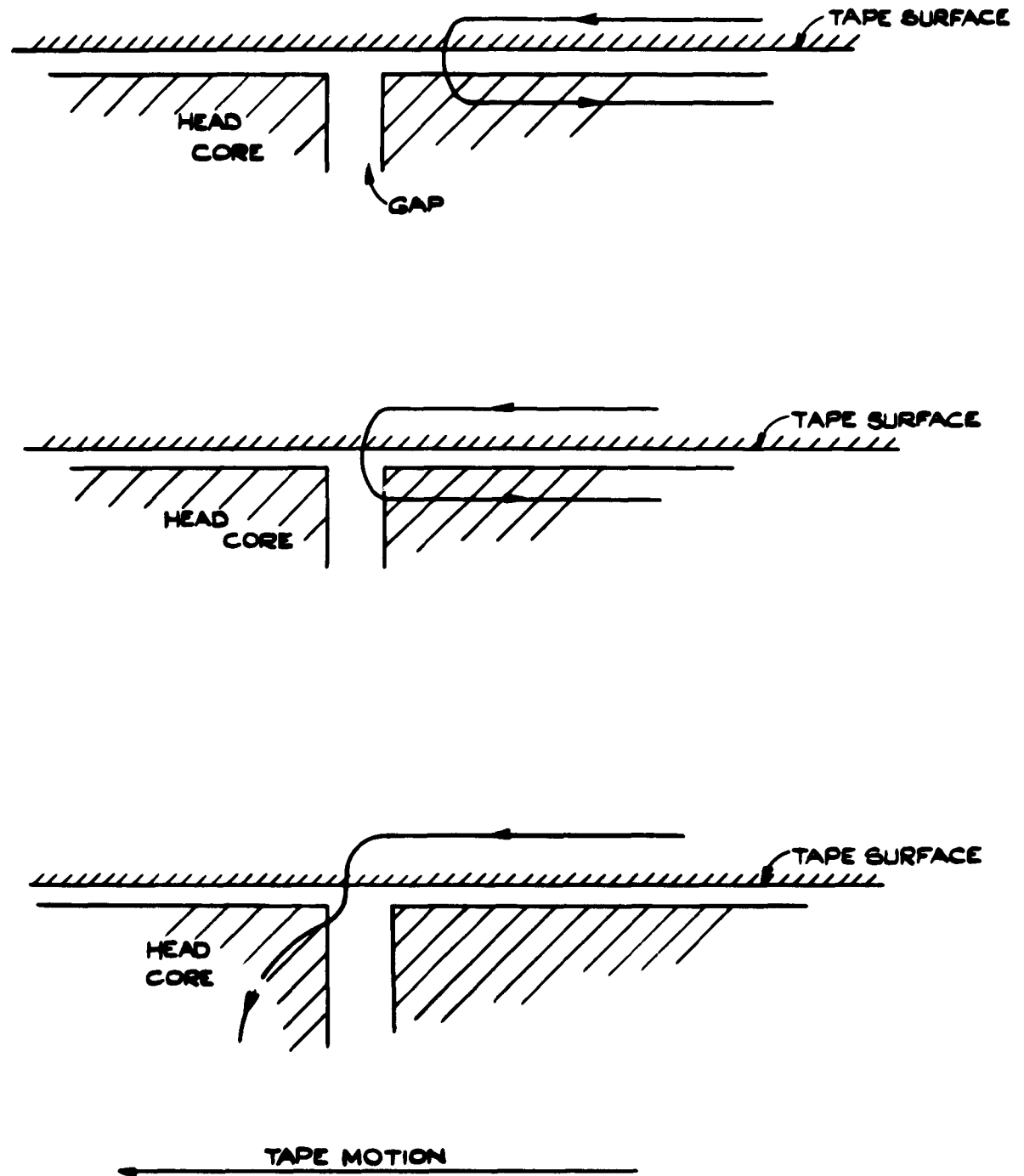
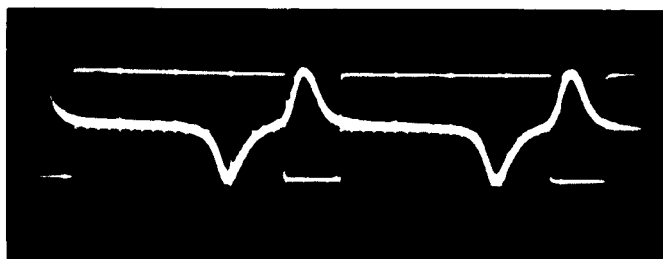
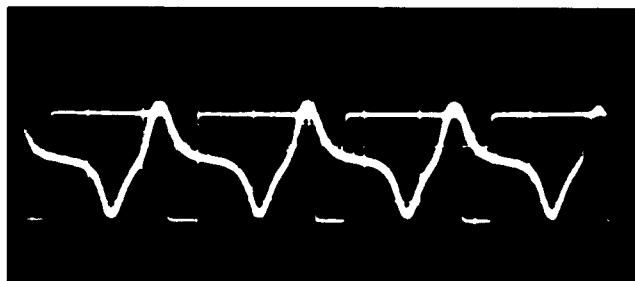


FIG.8 REPLAY PROCESS

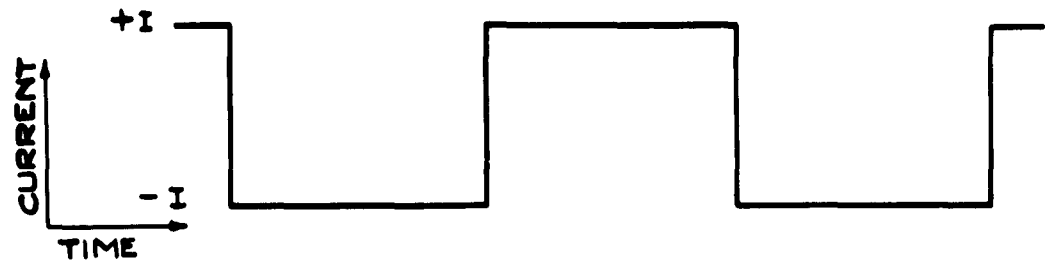


a. Theoretical pulse width 0.003 inch
represented by recording current

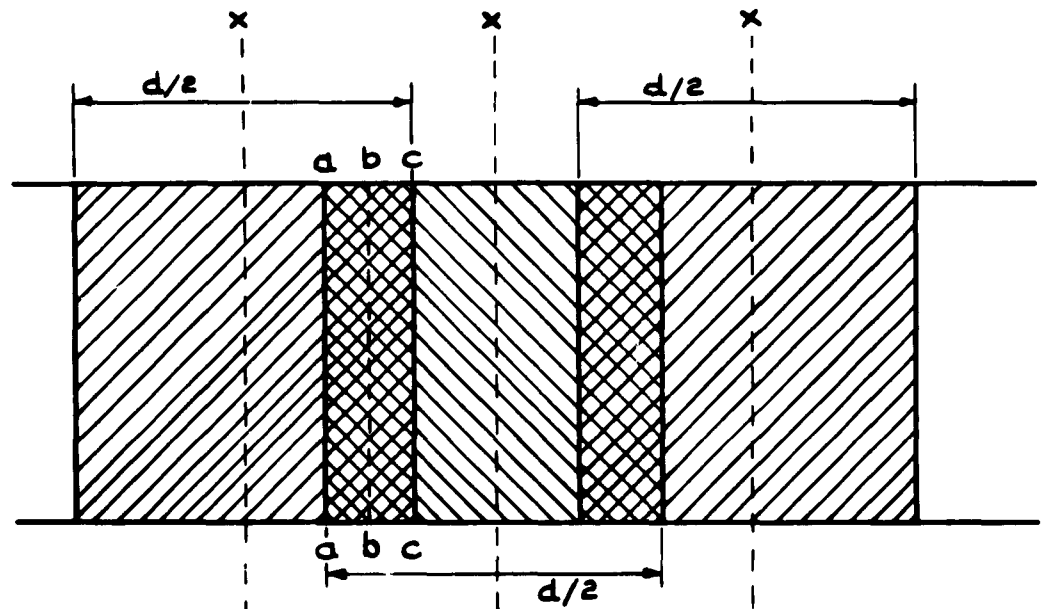


b. Theoretical pulse width 0.001 inch
represented by recording current

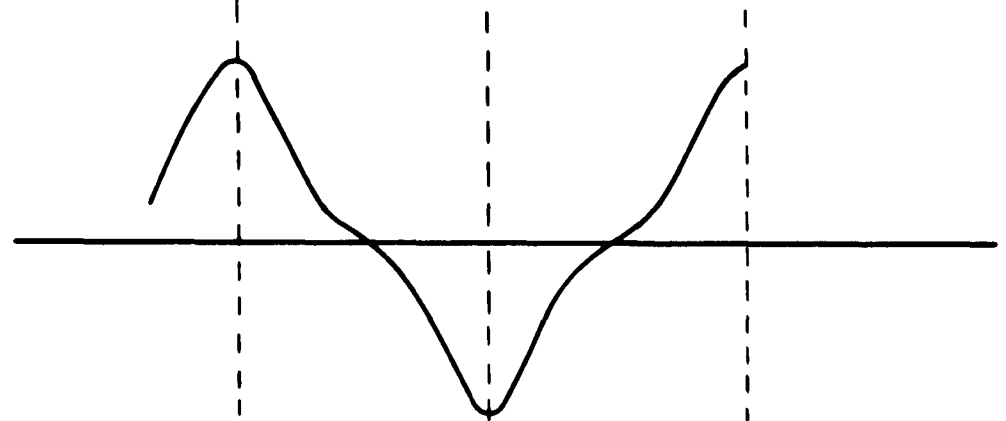
Fig.9 Pulse spreading in unidirectional recording



(a) RECORDING CURRENT



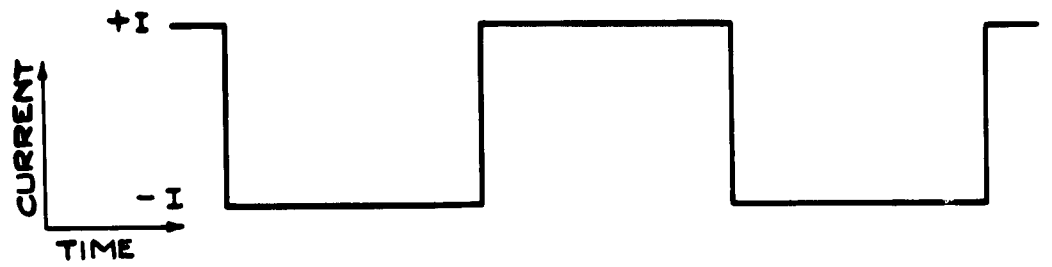
(b) PLAN VIEW OF NORMAL FLUX ON TAPE



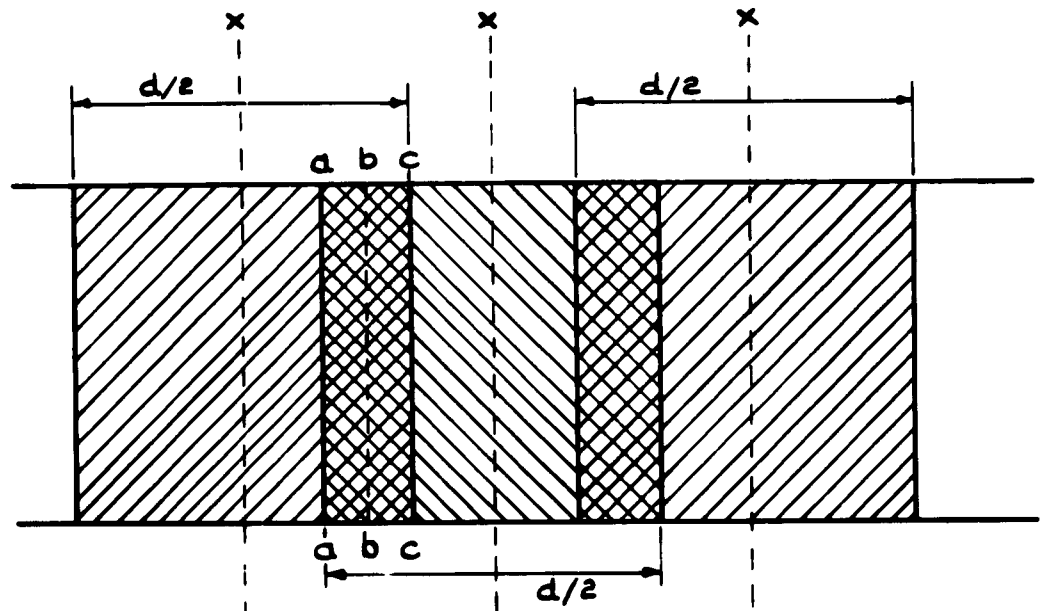
(c) REPLAY SIGNAL

← TAPE MOTION

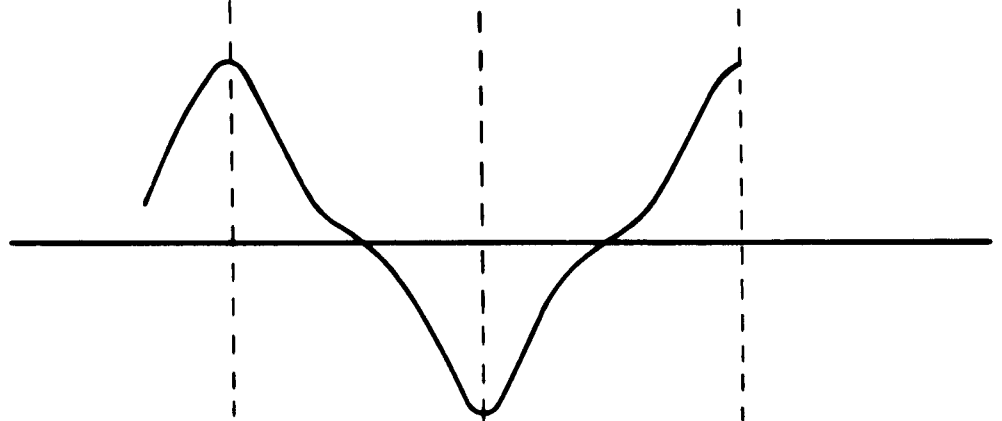
FIG.10(a-c) OVERLAP OF FLUX REVERSAL REGIONS



(a) RECORDING CURRENT



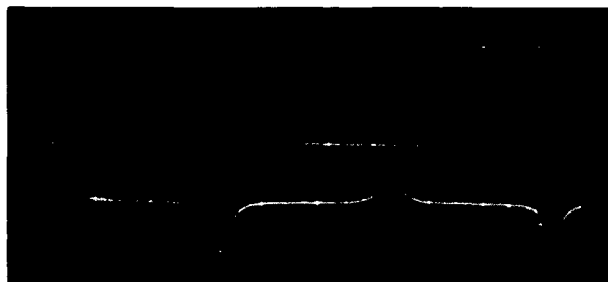
(b) PLAN VIEW OF NORMAL FLUX ON TAPE



(c) REPLAY SIGNAL

← TAPE MOTION

FIG.10(a-c) OVERLAP OF FLUX REVERSAL REGIONS



a. 200 flux reversals per inch



b. 1000 flux reversals per inch



c. 2000 flux reversals per inch

Fig.11 Replay signal for rectangular recording current

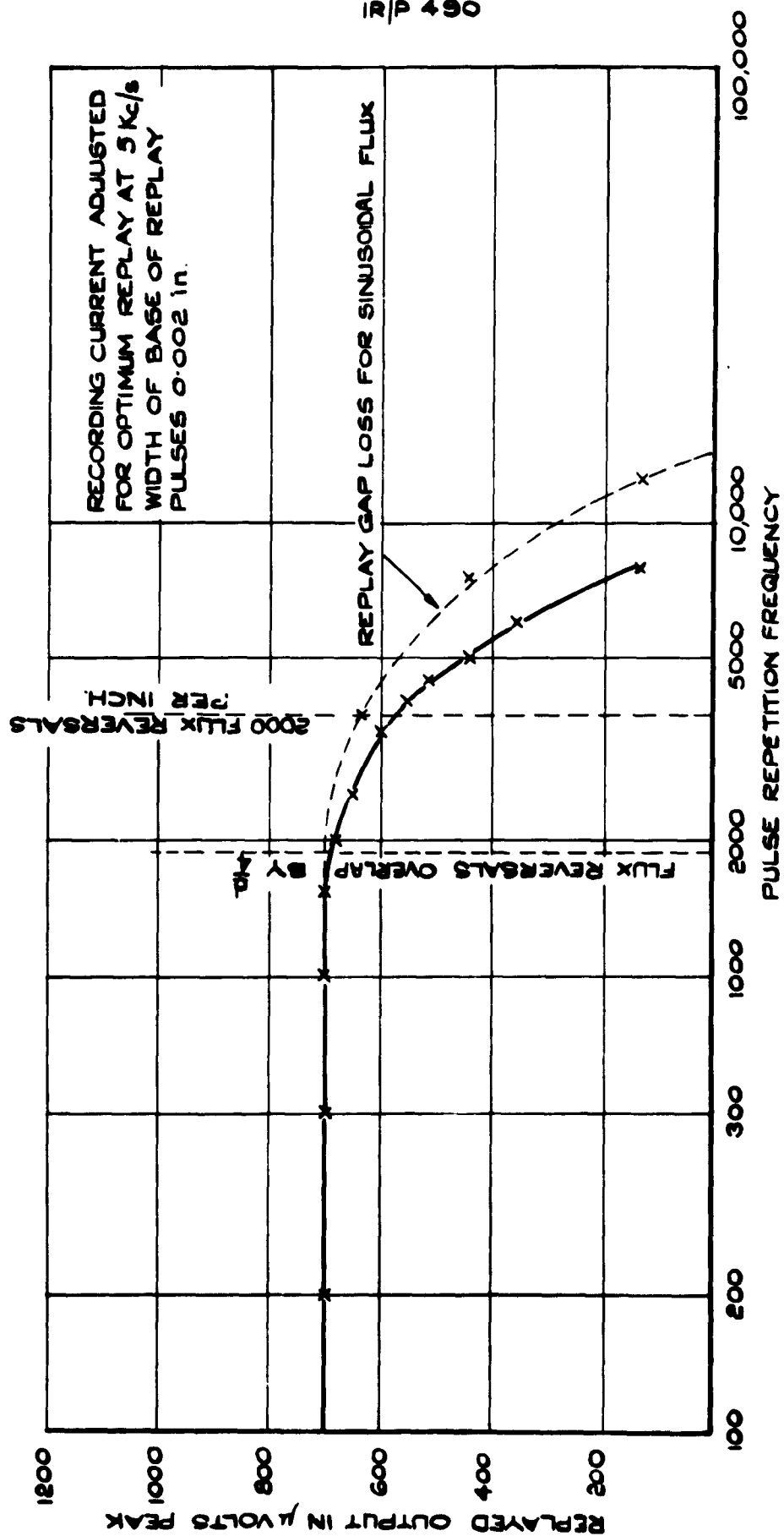


FIG.12 FREQUENCY RESPONSE FOR RECTANGULAR WAVE RECORDING
TAPE SPEED 3.75 in/sec

Fig.13

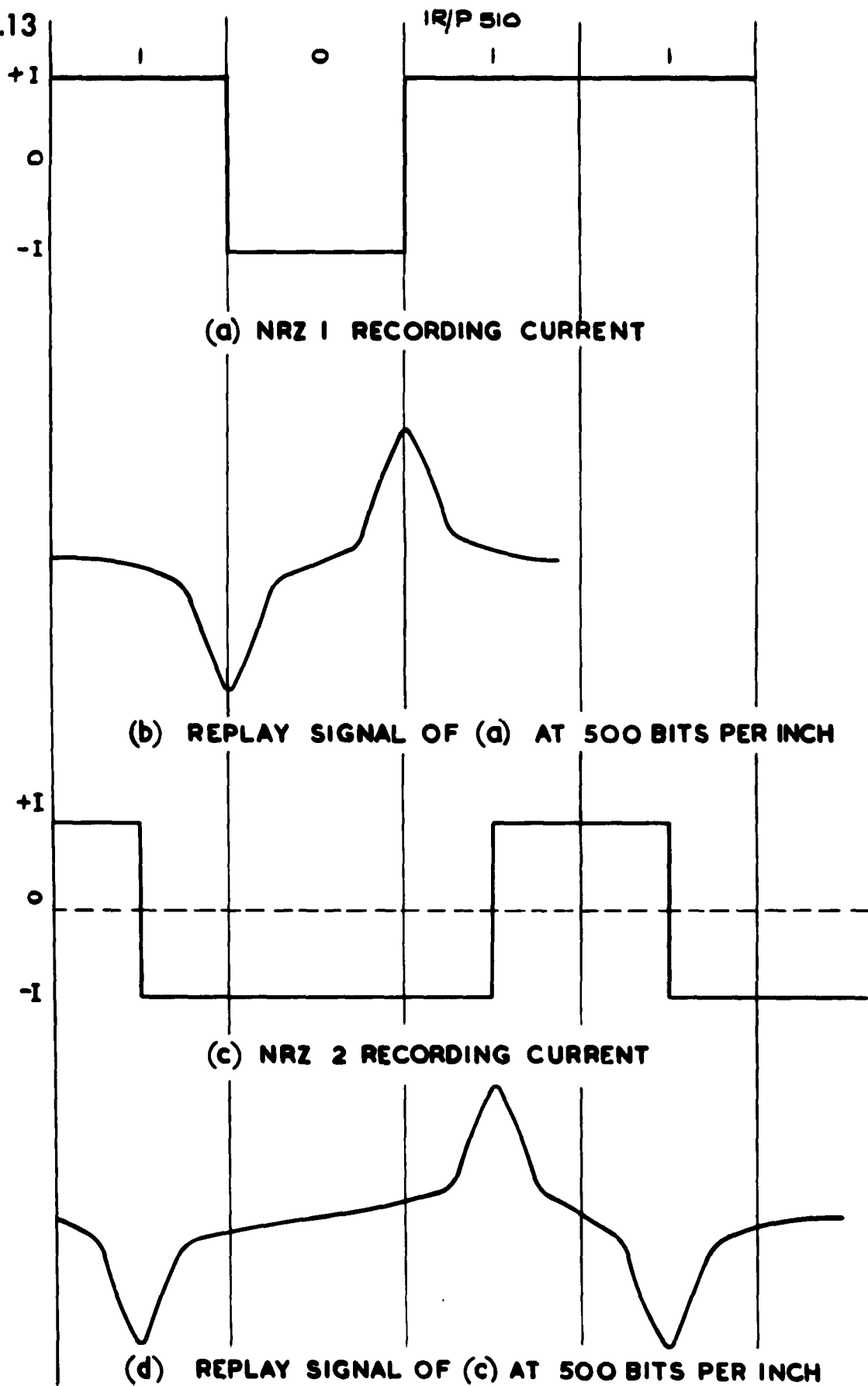


FIG 13 (a-d) NON-RETURN-TO-ZERO RECORDING

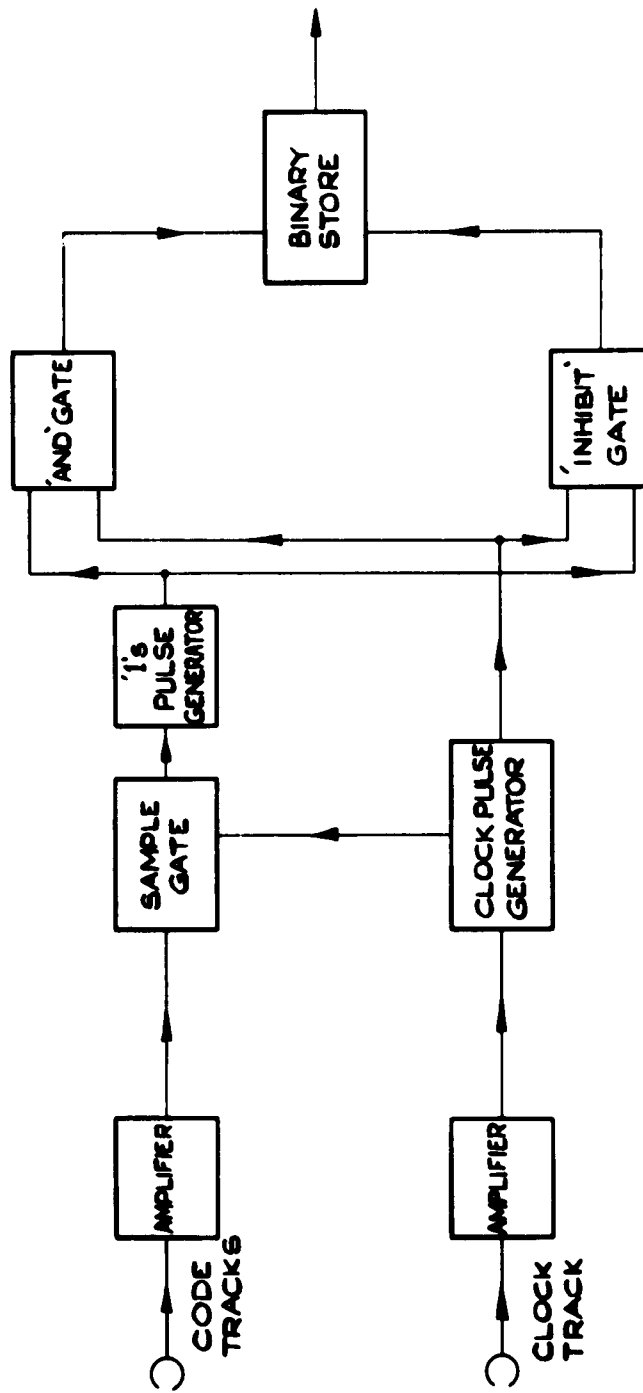
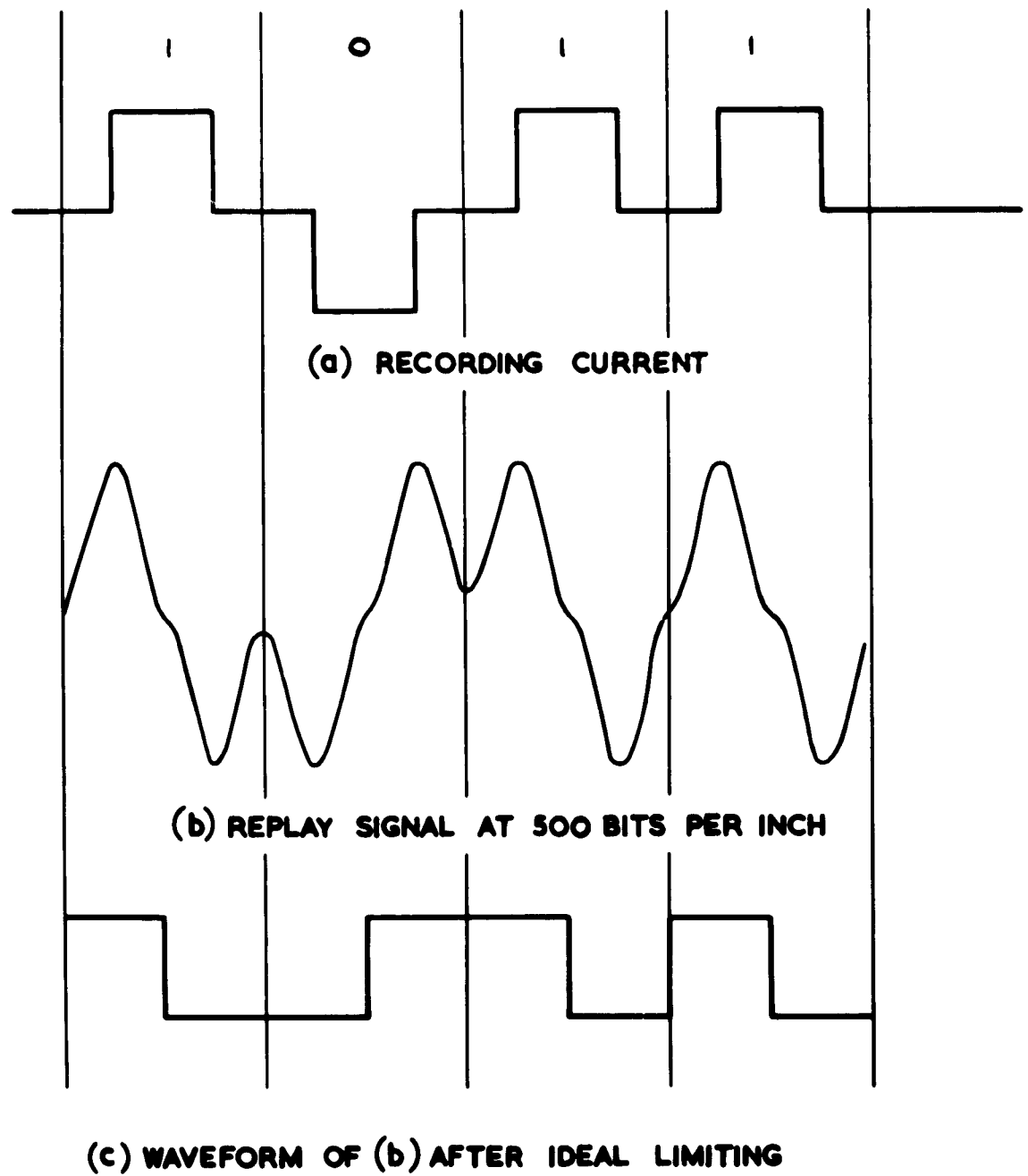
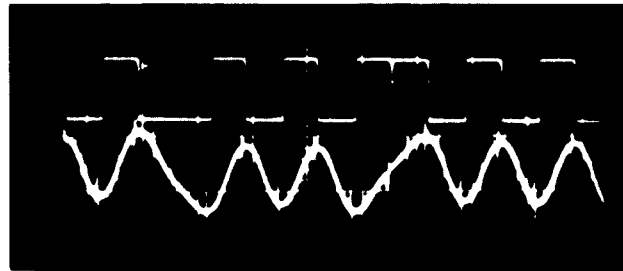
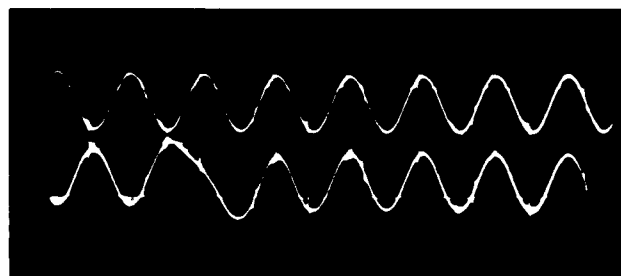


FIG.14 DECODING SYSTEM FOR NRZ RECORDING

**FIG.15(a-c) RETURN-TO-ZERO RECORDING**



a. Recording Current and Replay signal



b. Replay signals from a code track and clock track

Fig.17 Phase reversal recording

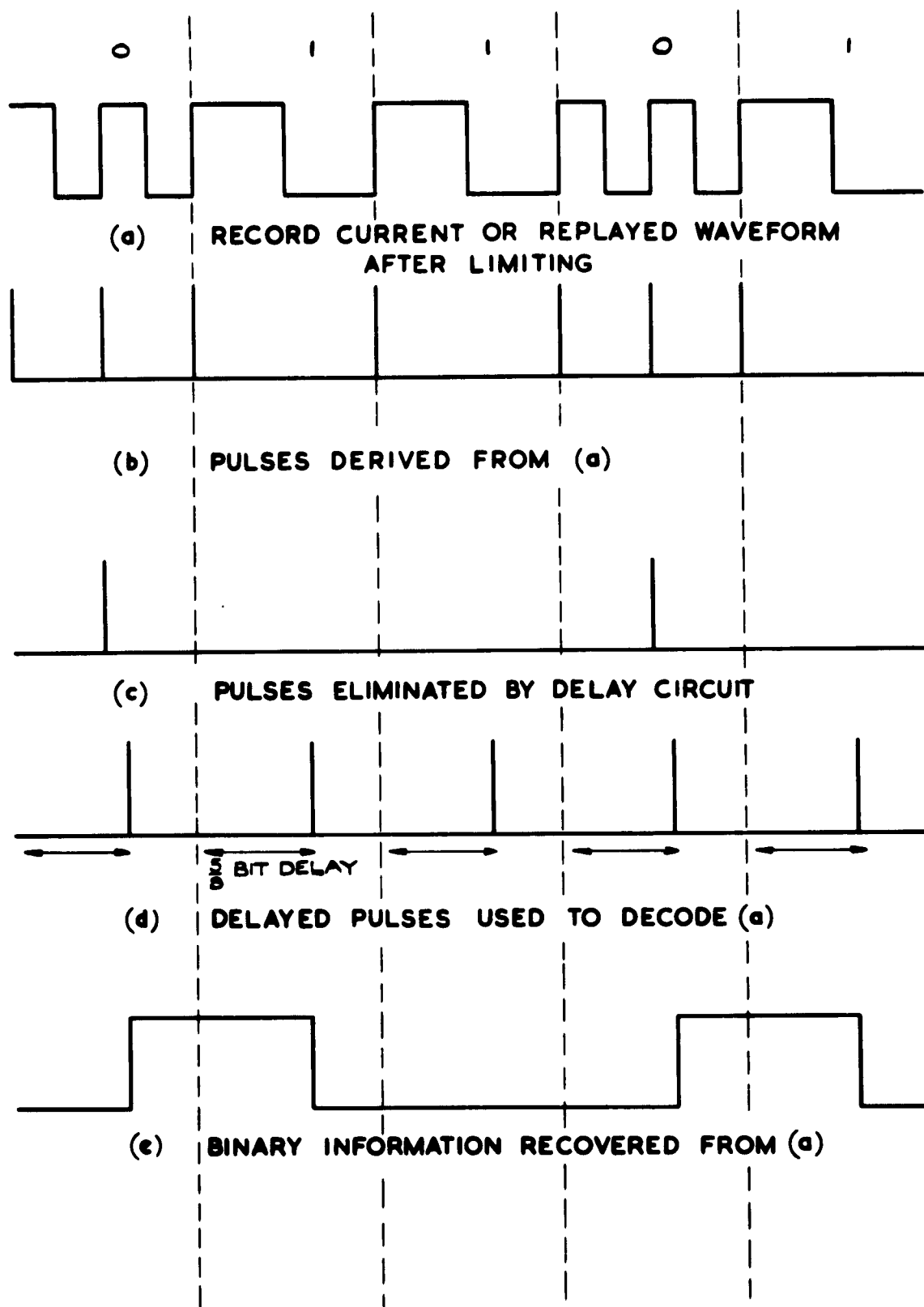


FIG.18 (a-e) TWO FREQUENCY SYSTEM. SELF-DECODING.

<p>Dingwall, P.F. Labrum, G.R.</p> <p>HIGH DENSITY DIGITAL RECORDING ON MAGNETIC TAPE</p> <p>Royal Aircraft Establishment Technical Report 65006</p> <p>January 1965</p> <p>The Report discusses the problems encountered in high area density digital recording on magnetic tape. Some aspects of the process of pulse recording are examined, and applied to the methods of digital recording in common use. A description is given of a system which offers advantages at high packing densities.</p>	<p>621.394.142 : 621.395.625.3 : 681.85</p>
<p>Dingwall, P.F. Labrum, G.R.</p> <p>HIGH DENSITY DIGITAL RECORDING ON MAGNETIC TAPE</p> <p>Royal Aircraft Establishment Technical Report 65006</p> <p>January 1965</p> <p>The Report discusses the problems encountered in high area density digital recording on magnetic tape. Some aspects of the process of pulse recording are examined, and applied to the methods of digital recording in common use. A description is given of a system which offers advantages at high packing densities.</p>	<p>621.394.142 : 621.395.625.3 : 681.85</p>